A new bound on $|U_{e3}|^2$ from CHOOZ data

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Consider the case of 3 massive ν_i:

$m_1 < m_2 < m_3$

Probability of $\nu_\alpha \to \nu_{\alpha'}$ in vacuum

$$P(\nu_\alpha \to \nu_{\alpha'}) = \left| \delta_{\alpha'\alpha} + \sum_{i=2}^{3} U_{\alpha' i} \left(e^{-i\Delta m_{i1}^2 \frac{L}{2E}} - 1 \right) U_{\alpha i}^* \right|^2$$

$$\Delta m_{i1}^2 = m_i^2 - m_1^2$$

Δm_{21}^2 is relevant for oscillations of solar neutrinos

Δm_{31}^2 is relevant for atm ν's oscillations

$$\Delta m_{21}^2 \ll \Delta m_{31}^2$$

Two main consequences of this inequality

(1) For atmospheric and LBL values of L/E

$$\Delta m_{21}^2 \frac{L}{2E} \ll 1$$

atm, LBL

$$P(\nu_\alpha \to \nu_{\alpha'}) \simeq |\delta_{\alpha'\alpha} + U_{\alpha'3} U^*_{\alpha 3}(e^{-i\Delta m^2_{31}\frac{L}{2E}} - 1)|^2$$

only $U_{\alpha 3}$ and Δm^2_{31} determine oscillations

<u>For transitions $\alpha' \neq \alpha$</u>

$$P(\nu_\alpha \to \nu_{\alpha'}) = \frac{1}{2} A_{\alpha'\alpha}(1 - \cos\Delta m^2_{31}\frac{L}{2E})$$

$$0 \leq A_{\alpha'\alpha} = 4|U_{\alpha'3}|^2 |U_{\alpha 3}|^2 \leq 1$$

<u>For survival probability $\alpha' = \alpha$</u>

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \frac{1}{2} B_{\alpha\alpha}(1 - \cos\Delta m^2_{31}\frac{L}{2E})$$

$$0 \leq B_{\alpha\alpha} = \sum_{\alpha' \neq \alpha} A_{\alpha'\alpha} = 4|U_{\alpha 3}|^2(1 - |U_{\alpha 3}|^2) \leq 1$$

Notice only $|U_{\alpha 3}|^2$ enters, no phase

$P(\nu_\alpha \to \nu_{\alpha'}) = P(\bar{\nu}_\alpha \to \bar{\nu}_{\alpha'})$ is <u>satisfied automatically</u>

CP violation can not be revealed in the case of Δm^2_{31} dominance

② consequence of $\Delta m^2_{31} \gg \Delta m^2_{21}$

$|U_{e3}|^2$ enters incoherently in the survival probability of solar ν_e's

$$P^{sol}(\nu_e \to \nu_e) = |U_{e3}|^4 + (1-|U_{e3}|^2)^2 \, P^{(1,2)}(\nu_e \to \nu_e)$$

$$\Delta m^2_{21}, \theta_{12}$$

$$\cos^2\theta_{12} = \frac{|U_{e1}|^2}{\sum_{i=1,2} |U_{ei}|^2}, \quad \sin^2\theta_{12} = \frac{|U_{e2}|^2}{\sum_{i=1,2} |U_{ei}|^2}$$

if $|U_{e3}|^2 \ll 1$

for solar neutrinos

$$P^{sol}(\nu_e \to \nu_e) \simeq P^{(1,2)}(\nu_e \to \nu_e)$$

information on $\Delta m^2_{21}, \theta_{12}$

$\nu_e \to \nu_\mu, \nu_\tau$ transitions

atm, LBL experiments

$\nu_\mu \to \nu_\tau$

information on $\Delta m^2_{31}, \theta_{23}$

correspond to observation

corrections to this picture?

Direct inf on $|U_{e3}|^2$ from LBL CHOOZ experiment

in the case of Δm^2_{31} dominance

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2} B_{ee} \left(1 - \cos \Delta m^2_{31} \frac{L}{2E}\right)$$

$$B_{ee} = 4|U_{e3}|^2 (1 - |U_{e3}|^2) = \sin^2 2\theta$$

From the CHOOZ exclusion curve

$$B_{ee} \leq B^0_{ee} (\Delta m^2_{31}) \qquad \text{Fig}$$

Two bounds on $|U_{e3}|^2$ $\quad \Delta m^2_{31} \geq 3 \cdot 10^{-2}$ $\quad B^0_{ee} \leq 10^{-1}$

$$|U_{e3}|^2 \leq \frac{1}{2}\left(1 - \sqrt{1 - B^0_{ee}}\right) \simeq \frac{1}{4} B^0_{ee} \ll 1$$

$$|U_{e3}|^2 \geq \frac{1}{2}\left(1 + \sqrt{1 - B^0_{ee}}\right) \simeq 1 - \frac{1}{4} B^0_{ee} \simeq 1.$$

if $|U_{e3}|^2 \simeq 1$, $P^{sol}(\nu_e \to \nu_e) \simeq 1$, thus $|U_{e3}|^2$ is small

$$\underline{|U_{e3}|^2 \leq 2.5 \cdot 10^{-2}}$$

from S-K spectrum measurement and D/N <u>LMA is the most preferred allowed region</u>

after SNO <u>the preference of LMA increased</u>

for LMA Δm^2_{21} can be $\underline{(\text{a few}) 10^{-4}\, eV^2}$

in the CHOOZ experiments

$L \simeq 1000\, m, \; E \simeq 3\, MeV$

$$\Delta m^2_{31} \frac{L}{2E} \simeq 0.8 \cdot 10^{-1}$$

<u>corrections to CHOOZ bound on</u>

<u>$|U_{e3}|^2$?</u>

$$P(\bar\nu_e \to \bar\nu_e) = 1 - 2|U_{e3}|^2 (1-|U_{e3}|^2)(1-\cos \Delta m^2_{31} \frac{L}{2E})$$

$$\underbrace{-2|U_{e2}|^2 |U_{e1}|^2 (1-\cos \Delta_{21})}$$

$$\underbrace{+2|U_{e3}|^2 |U_{e2}|^2 (\cos(\Delta_{31}-\Delta_{21}) - \cos \Delta_{31})}$$

additional terms

Fig

at $\Delta m^2_{21} \leq 4 \cdot 10^{-4}\, eV^2$ no changes

$\underline{\sin^2\theta_{12} \simeq \frac{1}{2}}$

at $\Delta m^2_{21} = 6 \cdot 10^{-4}\, eV^2 \quad |U_{e3}|^2 \leq 2 \cdot 10^{-2}$

$\Delta m^2_{21} = 8 \cdot 10^{-4}\, eV^2 \quad |U_{e3}|^2 \leq 1 \cdot 10^{-2}$

More exact determination of LMA allowed region

(S-K, SNO, KamLand, Borexino, ..)

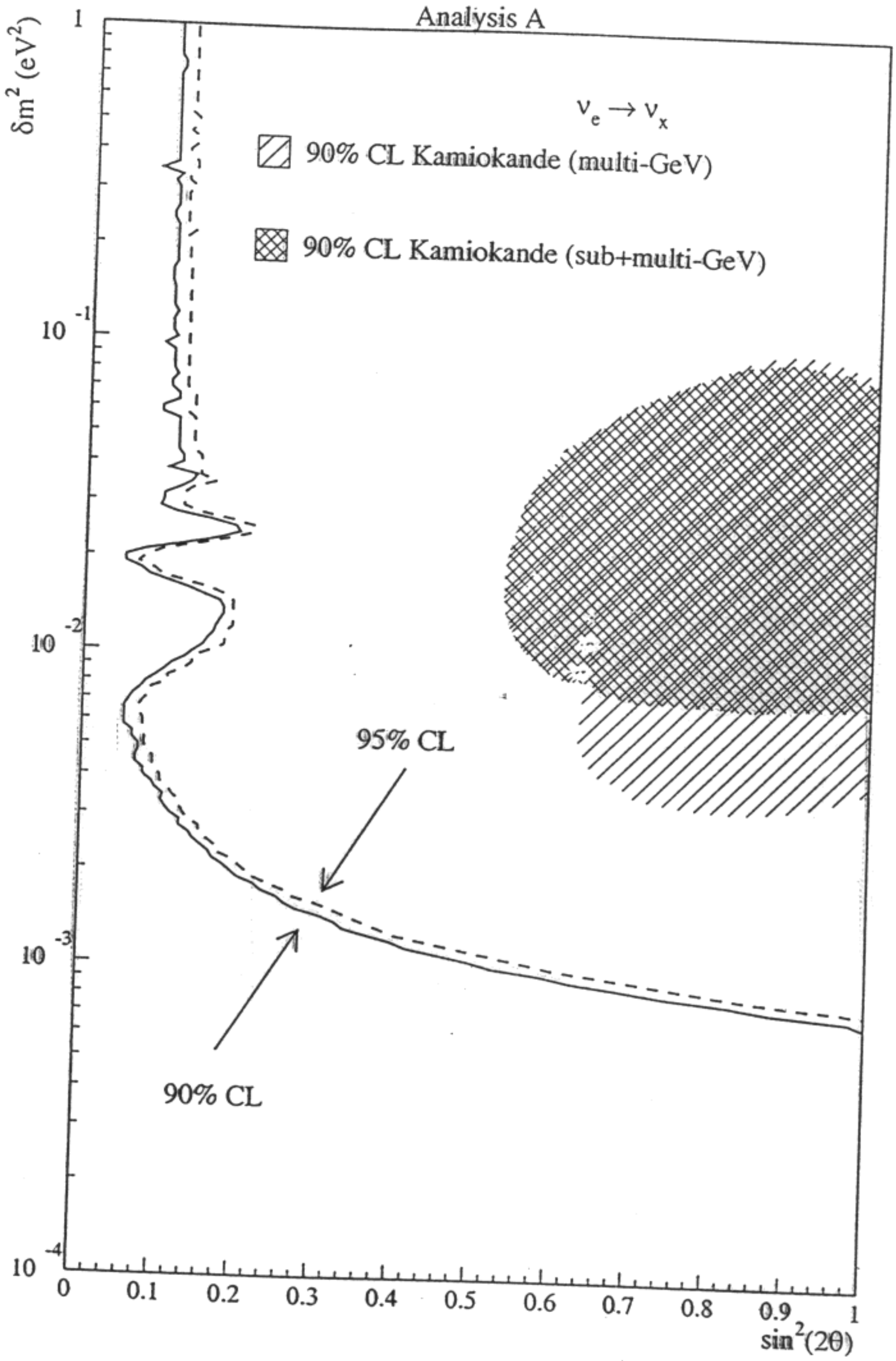
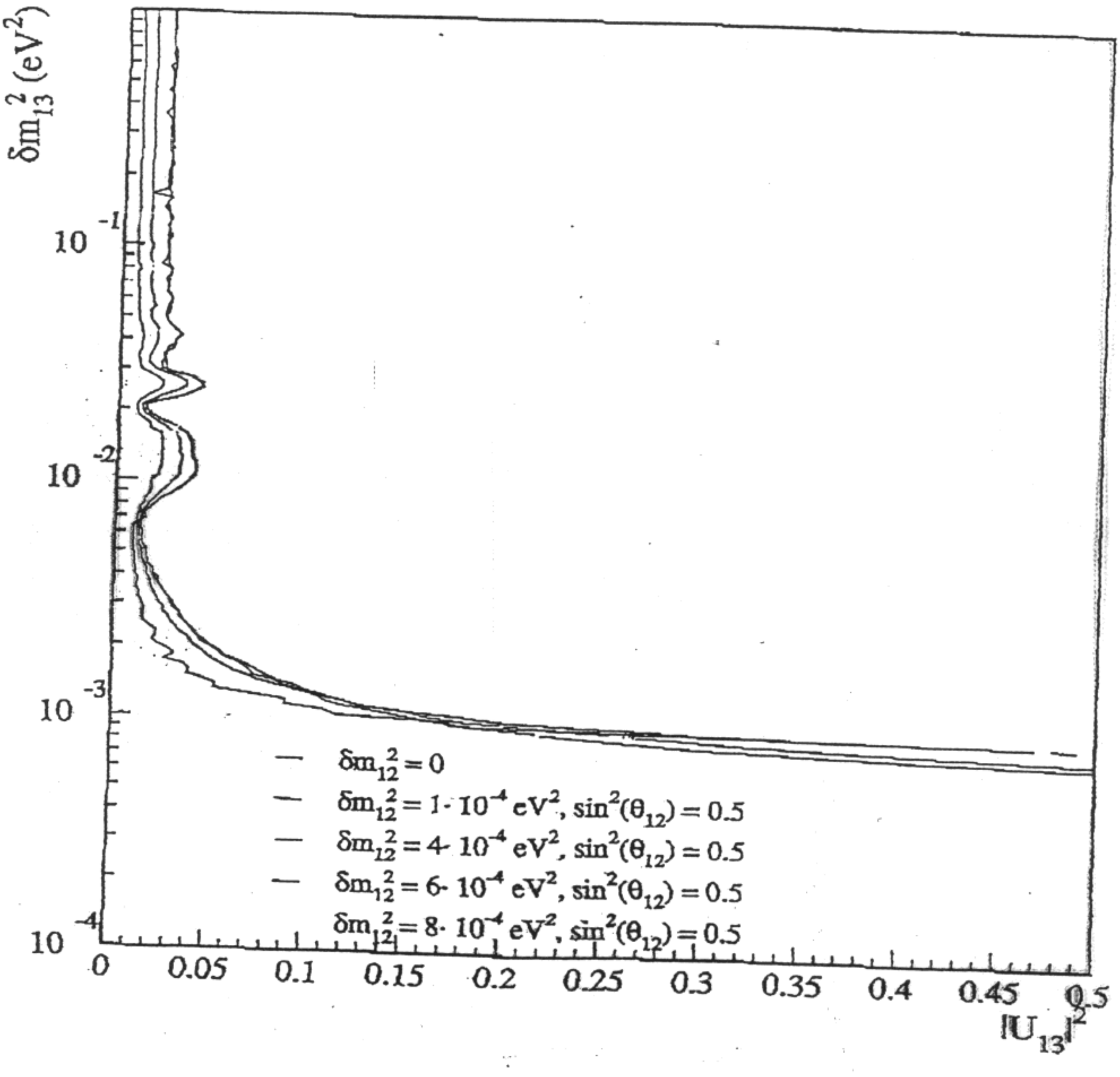


Figure 9: Exclusion plot for the oscillation parameters based on the absolute comparison of measured vs. expected positron yields.



$\delta m_{13}^2\ (eV^2)$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
$|U_{13}|^2$
$\delta m_{12}^2 = 0$
$\delta m_{12}^2 = 1\cdot 10^{-4}\ eV^2,\ \sin^2(\theta_{12}) = 0.5$
$\delta m_{12}^2 = 4\cdot 10^{-4}\ eV^2,\ \sin^2(\theta_{12}) = 0.5$
$\delta m_{12}^2 = 6\cdot 10^{-4}\ eV^2,\ \sin^2(\theta_{12}) = 0.5$
$\delta m_{12}^2 = 8\cdot 10^{-4}\ eV^2,\ \sin^2(\theta_{12}) = 0.5$